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February 1981

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PREFACE

This research effort was sponsored by the Air Force Office of Scientific Research and is a continuation of research performed in 1979 under the summer faculty research program. This effort was begun in June 1980 and completed in January 1981.

The author would like to thank the Air Force Systems Command and the Air Force Office of Scientific Research for providing him with the opportunity to participate in a most worthwhile program.

Special acknowledgement is due to those at Air Force Engineering and Services Center at Tyndall Air Force Base, Florida, for their cooperation and assistance, and for providing a pleasant working environment. The author is especially indebted to Lt. Col. Robert Boyer, Lt. Col. Roger Caldwell, Major Michael Carter, Robert Van Orman, Phillip Nash, and Capt. Michael McNerney for their continuous encouragement and guidance.

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AFOSR-TR- 89-1520

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

Traditional design and analysis of airport pavements are based on static wheel loads. But measurements of landing gear forces during various aircraft modes of operation have shown that pavements are subjected to dynamic loads of higher magnitude than the static load. However, because of the relatively slow response of pavement materials, these higher magnitude dynamic loads are neglected in pavement design. Field observations reinforce the use of static load for pavement design since areas of airfield pavements subjected to static and low speed modes of aircraft operation generally show more distress than areas of runways limited to medium and high speed aircraft operations.

Field test results from rapidly repaired bomb damaged runways, however, indicate unusually high magnitude dynamic loads due to increased surface roughness of the repaired runway. Preliminary data from the first phase of the Air Force's "Have Bounce" testing program have shown that dynamic main gear loads can be as high as 2.5 times the corresponding static aircraft loads (Reference 1).

Current research efforts in the Air Force Bomb Damage Repair Program concentrate on the effects of these high magnitude dynamic loads on the aircraft structure, aircraft payload, and pilot performance. But pavement response to these high magnitude dynamic loads must also be investigated. Specifically, a non-traditional dynamic analysis of pavement is needed in order to

evaluate the structural adequacy of rapid runway repairs. Such an analysis was initiated by the author while participating in the Air Force's Summer Faculty Research Program at the Engineering and Service Center, Tyndall Air Force Base, Florida. The results of this initial research effort are reported in the final report entitled "Response of Airfield Pavement to Large Magnitude Dynamic Loads" (Reference 2).

The purpose of this investigation is to continue the research initiated on the dynamic analysis of rapid runway repairs subjected to large magnitude loads. This research effort includes continuing a search of the literature, analytical work utilizing the computer, and experimental work. Specifically, this report addresses:

1. Developing a relationship for duration of load with aircraft and pavement parameters. Such a relationship is needed for dynamic testing of airfield pavement material properties.
2. Experimental testing of the dynamic behavior of polymer concrete. Since a search of the literature revealed that the dynamic behavior of polymer concrete had not been investigated, this research effort required experimental work.
3. Analysis of rigid and granular rapid runway repairs. The response of polymer concrete, sulfur concrete, and crushed stone repairs subjected to high magnitude dynamic loads is needed to design and analyze field tests using load carts and aircraft.

SECTION II

RELATIONSHIP OF LOAD DURATION WITH AIRCRAFT AND PAVEMENT PARAMETERS

Material properties needed for dynamic airfield pavement analysis depend on the duration of loading. It has been shown that duration of loading for a moving wheel load, T, can be determined from aircraft velocity and the half-wavelength of stress distribution obtained from a static stress analysis (Reference 2). The relationship is:

$$T = \frac{2\lambda}{V} \qquad (1)$$

where:

T = duration of load, in seconds
λ = half the wavelength of static stress distribution, in inches
V = aircraft velocity, in inches per second

Results from previous work showed considerable variation of λ for various aircraft and pavement systems (Reference 2).

The purpose of this section is to formulate a relationship for λ which includes aircraft and pavement parameters so that duration of loading, which is needed to determine dynamic material properties, can be computed for different aircraft and pavement systems.

1. λ DEFINED

Figure 1 shows a typical stress distribution for tensile stresses for the bottom of a rigid pavement slab as determined from a static stress analysis. For a moving wheel load, the

static stress distribution can be visualized as moving through the pavement system with time. The vertical axis in Figure 1 is stress, the horizontal axis represents distance for a static analysis, or time for a dynamic analysis (Equation (1) relates distance and time).

A cosine curve is used to represent this stress distribution for dynamic testing of materials. Figure 1 shows two cosine curves superimposed on the pavement stress distribution. The cosine curve having the same half-wavelength, λ', as the slab stress distribution is not a good representation of pavement stresses. The second cosine curve, by definition, intersects the pavement stress distribution at one-half the maximum stress and better represents the higher magnitude stress. An accurate simulation of the higher stress magnitudes is most important when testing dynamic material properties such as resilient modulus and fatigue life. For example, in testing the modulus of rupture of portland cement concrete, ASTM allows using any loading rate for loading up to 50% of the failure load. However, the modulus of rupture is sensitive to the rate of loading used from one-half the failure load to failure.

Decker (Reference 3) has summarized fatigue testing of asphalt concrete using square, cosine, and triangular loading waveforms. Specimens subjected to the square-waveform loading had less than one-half the fatigue life of identical specimens loaded with the cosine-waveform; the use of the triangular-waveform

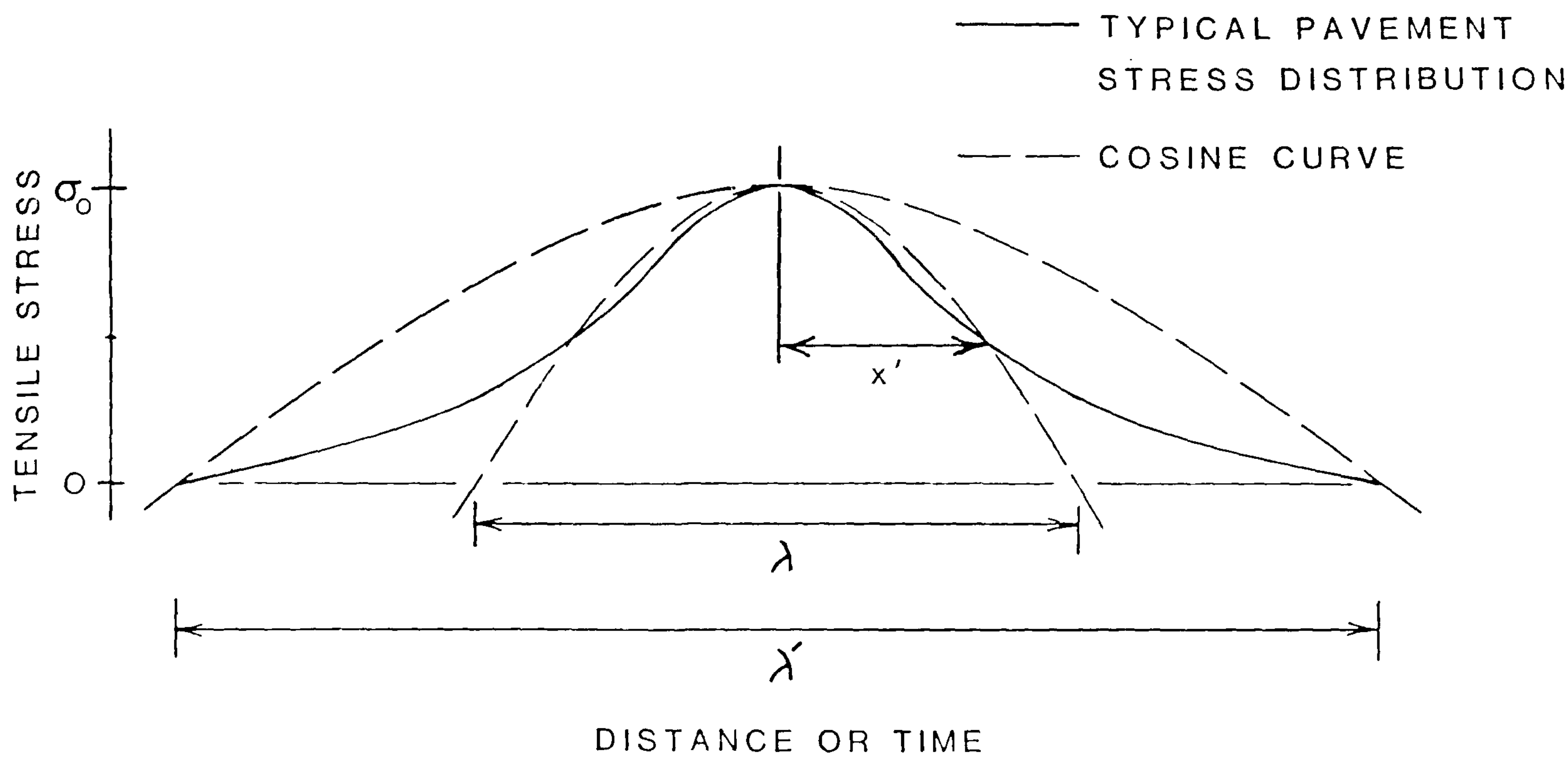

Figure 1. Tensile Stress Distribution for Bottom of Rigid Slab

loading resulted in a 45 percent increase in fatigue life as compared to the cosine loading. Frequency and maximum stress amplitude were held constant for the test. The square-waveform loading has the fastest rate of loading, but the maximum stress is applied for the entire load cycle, whereas it is only applied for an instant for the triangular loading. The duration of the higher magnitude portion of the load apparently dominates the behavior.

To determine λ using the cosine curve yielding a better fit, the static stress distribution as a function of x used is

$$\sigma_x = \sigma_o \cos \frac{\pi x}{\lambda} \tag{2}$$

where σ_o is the maximum stress at x = 0.

From Figure 1, x' is defined as the horizontal distance from the center of the wheel load where the stress, σ_o, is a maximum to the point where the stress is one-half the maximum. Therefore, substituting $\sigma_x = \sigma_o/2$ and $x = x'$ into Equation (2) and solving for λ:

$$\frac{\sigma_o}{2} = \sigma_o \cos \frac{\pi x'}{\lambda} \tag{4}$$

from which

$$\lambda = 3x' \tag{5}$$

From the results of static stress pavement analysis, x' can be computed and λ solved for.

2. RELATIONSHIP OF λ WITH AIRCRAFT AND PAVEMENT PARAMETERS

The BDR computer code developed by the Air Force was used for static pavement analysis to determine x', and thus λ, for various

aircraft and pavement systems. The BDR computer code is the most recent and sophisticated pavement analysis computer program developed by the Air Force. Twenty-four aircraft-pavement systems were analyzed using several slab thicknesses, subgrade moduli, aircraft tire pressures, and gross weights. The pavement and aircraft variables used for the analysis are listed in Table 1 along with the maximum tensile slab stresses and the half-wavelengths, λ, as previously defined.

Multiple regression analysis was used to relate the half-wavelength corresponding to the horizontal stress at the bottom of a slab, λ_s, with aircraft and pavement parameters. After preliminary analysis using several aircraft parameters, it was found that the radius of tire footprint, R, correlated best with λ_s for a given pavement. The radius of tire footprint incorporates aircraft weight and tire pressure and is defined as

$$R = \sqrt{\frac{P}{\pi p}} \qquad (6)$$

where:

R = radius of tire footprint, in inches
P = weight on aircraft tire, in pounds
p = tire pressure, in psi

The characteristic length, L, was used to incorporate the parameters of pavement slab and subgrade. The characteristic length is defined as (Reference 4)

TABLE 1 - RESULTS OF BDR COMPUTER ANALYSIS OF RIGID PAVEMENT

Subgrade Modulus (psi)	Aircraft Wheel Load (kips)	Aircraft Tire Pressure (psi)	Maximum Tensile Stress (psi)	λ (inches)
		8 inch thick slab		
10,000	13.5	265	199	31.6
10,000	27.0	265	348	35.1
10,000	40.5	265	474	36.9
10,000	54.0	265	583	39.3
10,000	81.0	265	768	43.4
10,000	27.0	130	290	39.4
10,000	54.0	130	459	46.8
10,000	81.0	130	584	50.8
10,000	47.0	150	442	43.8
10,000	94.0	150	676	50.8
10,000	141.0	150	846	55.8
5,000	27.0	265	393	38.2
5,000	54.0	265	658	42.3
5,000	81.0	265	870	46.1
30,000	27.0	265	278	30.0
30,000	54.0	265	455	35.2
30,000	81.0	265	589	38.9
		5 inch thick slab		
10,000	27.0	265	621	26.6
10,000	54.0	265	970	31.2
10,000	81.0	265	1230	33.8
5,000	81.0	265	1434	36.2
		12 inch thick slab		
10,000	27.0	265	190	45.2
10,000	54.0	265	335	50.2
10,000	81.0	265	457	52.9

$$L = \sqrt[4]{\frac{E_s h^3}{12k(1-\mu_s)}} \qquad (7)$$

where:

L = characteristic length, in inches
E_s = modulus of slab material, in psi.
h = thickness of the slab, in inches
μ = Poisson's ratio of the slab material

After several multiple regression analyses, both linear and non-linear, the result yielding the highest correlation coefficient was

$$\lambda_s = 4.56 + 1.88R + 0.767L \qquad (8)$$

where, λ_s, R, and L, are all expressed in inches. The correlation coefficient squared was computed as 0.974 and the standard error of estimate was 1.30 inches. Equation (8) is shown graphically in Figure 2 along with the data from the computer analysis. A correlation coefficient squared of 0.974 indicates Equation (8) represents an excellent relationship between the variables. Of course the data used for the regression analysis was computer generated and therefore such a high correlation would not be expected using data from actual field tests.

A similar multiple regression analysis was used to relate the half-wavelength for the vertical subgrade stress, λ_{sub}, with R and L. Several different multiple regression analyses, linear and nonlinear, were performed. It was found that the influence of radius of tire footprint, R, was insignificant and the equation showing the highest correlation was

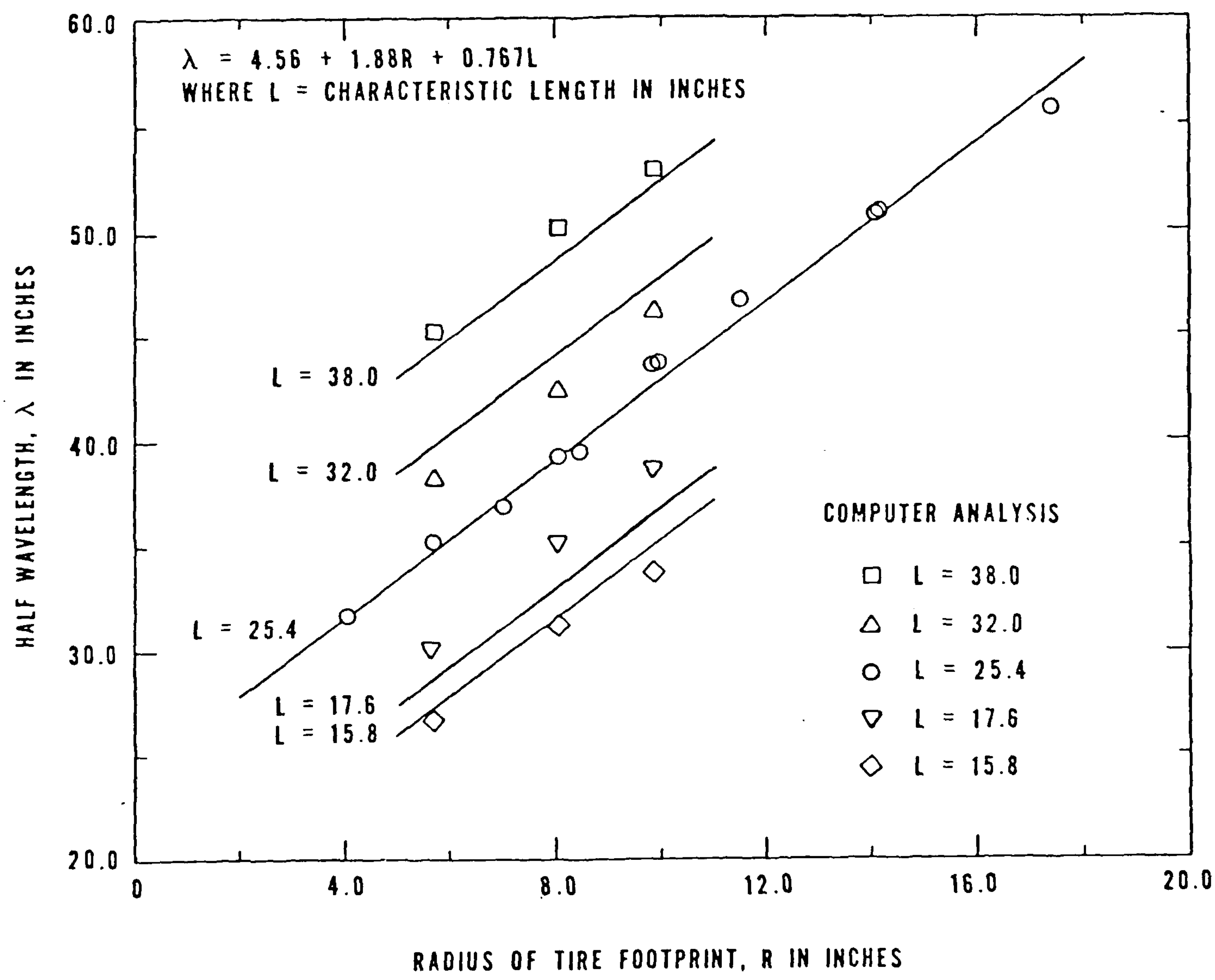

Figure 2. Multiple Linear Regression Results for Half Wavelength of Flexural Stress

$$\lambda_{sub} = 16.37 + 1.917L \qquad (9)$$

where λ_{sub} and L are both in inches.

The correlation coefficient squared for Equation (9) is 0.935. However, an analysis using actual field data would probably not yield as high a correlation.

In summary, for a given aircraft and pavement system, the equations developed in this section can be used to determine the load duration (and thus an estimate of rate of loading) for dynamic modului testing, or loading frequency for fatigue testing. Specifically, Equations (6) and (7) are used to calculate R and L for a given aircraft and pavement. Substituting R and L into Equation (8) for the pavement slab and Equation (9) for the subgrade, λ is computed. Using Equation (1), the duration of load, T, can be computed for various aircraft speeds. The rate of loading to be used for determining dynamic modului can be approximated by assuming the load increases from zero to maximum within one-half the load duration, T. (The rate of loading actually varies, decreasing to zero at maximum stress as shown in Figure 1.) The frequency of loading to be used for fatigue testing is simply the inverse of the duration of load, T.

SECTION III

DYNAMIC MODULUS AND FATIGUE TESTING OF POLYMER CONCRETE

The U.S. Air Force is investigating the use of polymer concrete for rapid repair of bomb damaged runways. A review of the literature revealed that the dynamic behavior of polymer concrete has not been investigated (References 5, 6, and 7). This section reports the results of a laboratory investigation undertaken to study the dynamic behavior of polymer concrete. In particular, the influence of rate of loading on the modulus of rupture, and the influence of loading frequency and rest periods on fatigue life was studied. Other parameters, such as mix proportions, specimen size, and temperature were held constant.

1. EXPERIMENTAL PROCEDURE

1.1 Materials Used

The polymer concrete used in this study was a special prepackaged Silikal® methyl methacrylate polymer concrete supplied by the U.S. Air Force. Silikal® polymer concrete is a proprietary prepackaged methyl methacrylate polymer concrete system manufactured by Silikal® North America and it's licensees. The prepackaged system consists of two components, one powder and one liquid. The powder component consists of fine quartz sand, powdered benzoyl peroxide initiator, pigment, powdered polymer for workability, and other proprietary additives. The liquid compo-

nent consists of liquid methyl methacrylate monomer, a promoter, and other proprietary additives. The powder component is mixed directly with the liquid component in a polyethylene mixing bag in premeasured quantities. This produces a concrete with mortar consistency. In this study, dry coarse aggregate was added to the mortar to extend the mortar to a consistency of normal concrete.

The special Silikal® polymer concrete used for this study is similar to the commercially available Silikal® R7 with special packaging to permit extended shelf-life. The Silikal® used was packaged in 15 kg bags, and seven beam specimens were made from each bag. All 7 bags used were from the same numbered lot and had been stored and shipped together.

The course aggregate was locally purchased river run gravel. The gravel was then washed, mechanically screened, and oven dried. For each 15 kg bag of powder, 15 kg of coarse aggregate was recombined in the following proportions: 5/8 inch to 1 inch, 6.25 kg; 5/16 inch to 5/8 inch, 5.0 kg; and 2 mm (#10 sieve) to 5/16 inch, 3.75 kg. Each batch of coarse aggregate was precisely weighed and thoroughly mixed. No aggregate finer than a #10 sieve was added because the prepackaged polymer concrete system contains all the fine aggregate required in the powder component.

1.2 Specimen Preparation

The beam specimens were cast at Tyndall AFB in batches of seven beams, and in general conformance to ASTM Making and Curing

Concrete Test Specimens in the Laboratory (C 192). A minor departure to the concrete standard was introduced by placing and rodding the polymer concrete in two lifts rather than three because of the size of the 3" x 3" x 11" beams. A thermocouple was inserted at one end of each beam to observe the time and temperature of the peak exotherm in each specimen as part of an anticipated quality control program. The intended purpose of this control was the identification of abnormal temperature rises which might serve as rejection criteria for atypical behavior, thereby effecting a reduction in the coefficient of variation for the flexural strength. At this time, however, such an analysis has not been performed, and there is no information on the effect on the coefficient of variation. To minimize the cure time or age difference of the specimens, all the beams were cast within a two day period at room temperature. At least 90 days elapsed between casting the specimens and testing. The specimens were tested at Marquette University.

1.3 Testing

The experimental program included testing for the modulus of rupture and fatigue behavior of polymer concrete beam specimens. An MTS testing machine with a 20 kip load cell was used for all testing. The MTS testing machine was fitted with supports for third-point loading. The supports conformed to ASTM Standard Test Methods for Flexural Strength of Concrete (Using Simple Beam with

Third-Point Loading) (C 78-75). Specimens were chosen for the various tests in a random manner. All tests were conducted at room temperature.

Modulus of Rupture Testing - The modulus of rupture testing was divided into static and dynamic loading. For the static load test, specimens were loaded in accordance with ASTM C78-75. Specifically, four specimens were loaded rapidly to 3 kips (less than 50 percent of the failure load), then loaded at a rate of 150 psi/min to failure. The maximum loads recorded from a digital voltmeter were 7.65, 6.27, 7.37, and 7.27 kips. The low reading of 6.27 kips was discarded and the mean of the remaining three values was calculated to be 7.43 kips. This value was used as the load corresponding to the modulus of rupture of the polymer concrete for calculating stress levels for the fatigue testing.

To determine if the rate of loading influenced the modulus of rupture of polymer concrete, four specimens were loaded at a rate of loading of 199,980 psi/min which was about the same rate of loading corresponding to fatigue loading at 0.5 c/s. Maximum loads determined to two significant figures from an osciloscope were 8.8, 8.3, 7.4 and 8.4 kips.

Fatigue Testing - For fatigue loading, all of the specimens were loaded with a haver-sine loading where the load varied between a maximum and minimum. The maximum load applied was a ratio of the modulus of rupture load of 7.43 kips determined from the static testing. The ratio is termed the stress level, S

(the ratio of flexural stresses is the same as the ratio of loads for a given specimen size and loading configuration). A minimum load of about 200 lbs was used to prevent stress reversals and to hold the specimens in place.

To determine the effect of certain parameters on the fatigue behavior of polymer concrete, specimens were divided into three groups: A, B, and C. Specimens from group A were loaded at a frequency of 0.5 c/s. Initially a stress level of 0.9 was used (maximum load at 90 percent of 7,43, or 6.69 kips), but after testing two specimens, it was decided to use lower stress levels. Four specimens were tested at a stress level of 0.8 and another four were tested at a stress level of 0.65.

Specimens of group B were used to determine if frequency of loading effects the fatigue life of polymer concrete. Specimens of group B were loaded at a frequency of 10 c/s, four specimens at a stress level of 0.8 and another four at a stress level of 0.65.

For most uses, polymer concrete would not be subjected to the type of continuous cyclic loading used in standard fatigue testing. In particular, for pavements, especially airport pavements, there would be a rest period between load pulses. For this reason, group C was used to determine if the inclusion of a rest period between each load pulse influenced fatigue life of polymer concrete. The loading used for group C had a load pulse duration of 0.1 sec., which was the same load pulse duration used for specimens of group B, which were loaded at a frequency of 10 c/s.

For group C, however, each load cycle included a rest duration of 0.9 sec during which the specimen was subjected only to the minimum load. The 0.1 sec load pulse followed by the 0.9 sec rest period gave a frequency of loading of 1 c/s. For group C, three specimens were tested at a stress level of 0.80 and four specimens at a stress level of 0.65.

The loading waveforms used for testing groups A, B, and C are shown in Figure 3. Results of the fatigue testing are listed in Table 2 and plotted in Figure 4.

2. ANALYSIS OF RESULTS

2.1 Modulus of Rupture Testing

Comparing results of the static and dynamic modulus of rupture testing, it was apparent that the rate of loading influenced the modulus of rupture of polymer concrete. Discarding the one low reading from the results of the dynamic test, the mean of the remaining three values was 15 percent higher than the results of the static modulus of rupture testing.

Rate of loading had a similar effect on the modulus of rupture of Portland Cement Concrete (PCC). McHenry (Reference 8) reported that as rate of loading increased from 1034 to 3477 kPa/min, the modulus of rupture of PCC increased by about 2 to 13 percent, depending on mix parameters, age at testing, etc.

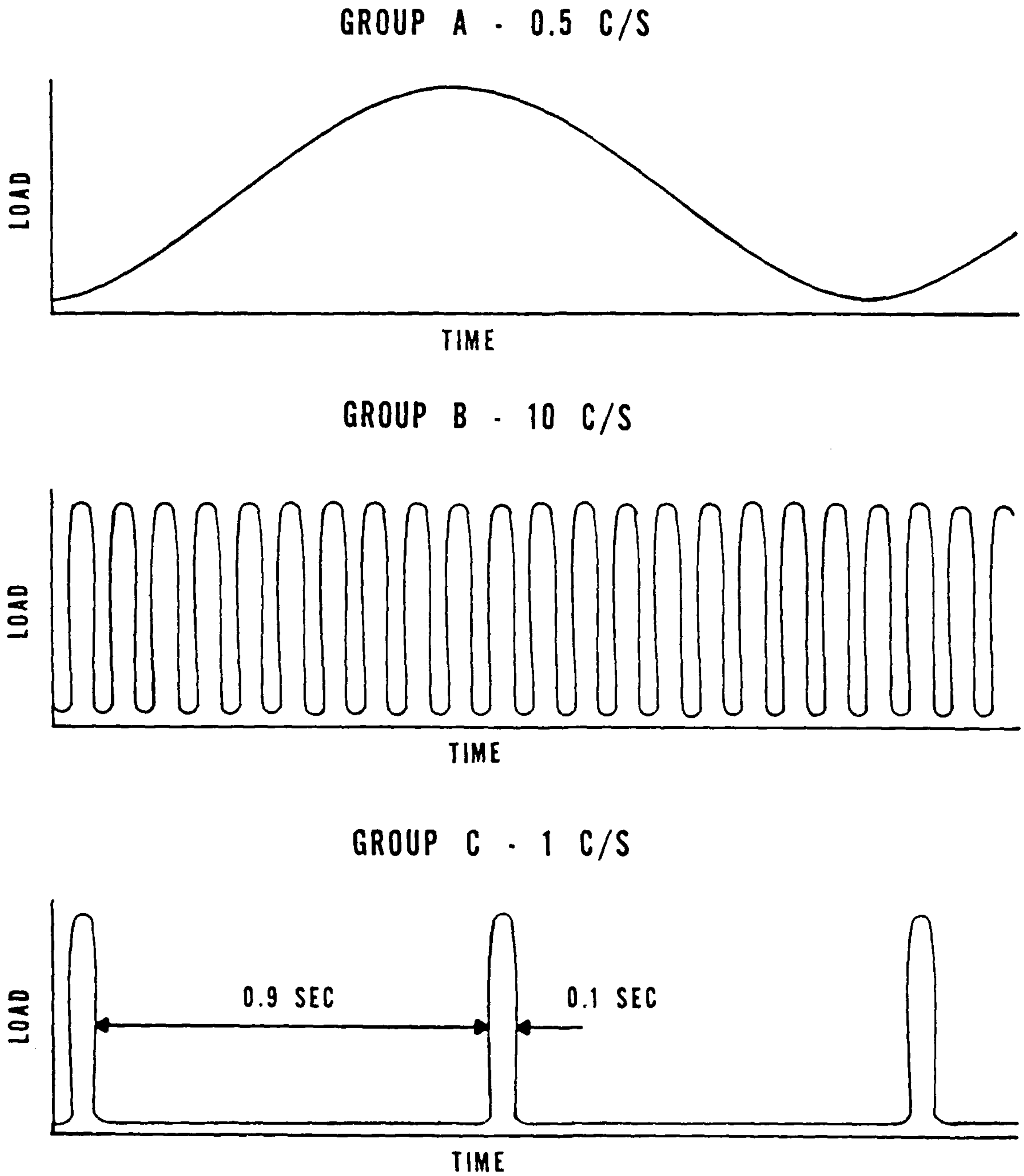

Figure 3. Loading Waveforms Used for Polymer Concrete Fatigue Testing

TABLE 2 - FLEXURAL FATIGUE LIFE OF POLYMER CONCRETE

Group	Number of Cycles to failure, N, for a given stress level, S.		
	S = .90	S = .80	S = .65
A	24	192	1,067
	172	689	2,039
		1,310	2,585
		1,678	13,784
B		90	36,310
		690	43,010
		1,290	72.690
		3,610	147,720
C		34	7,016
		278	21,417
		328	29,149
			85,381

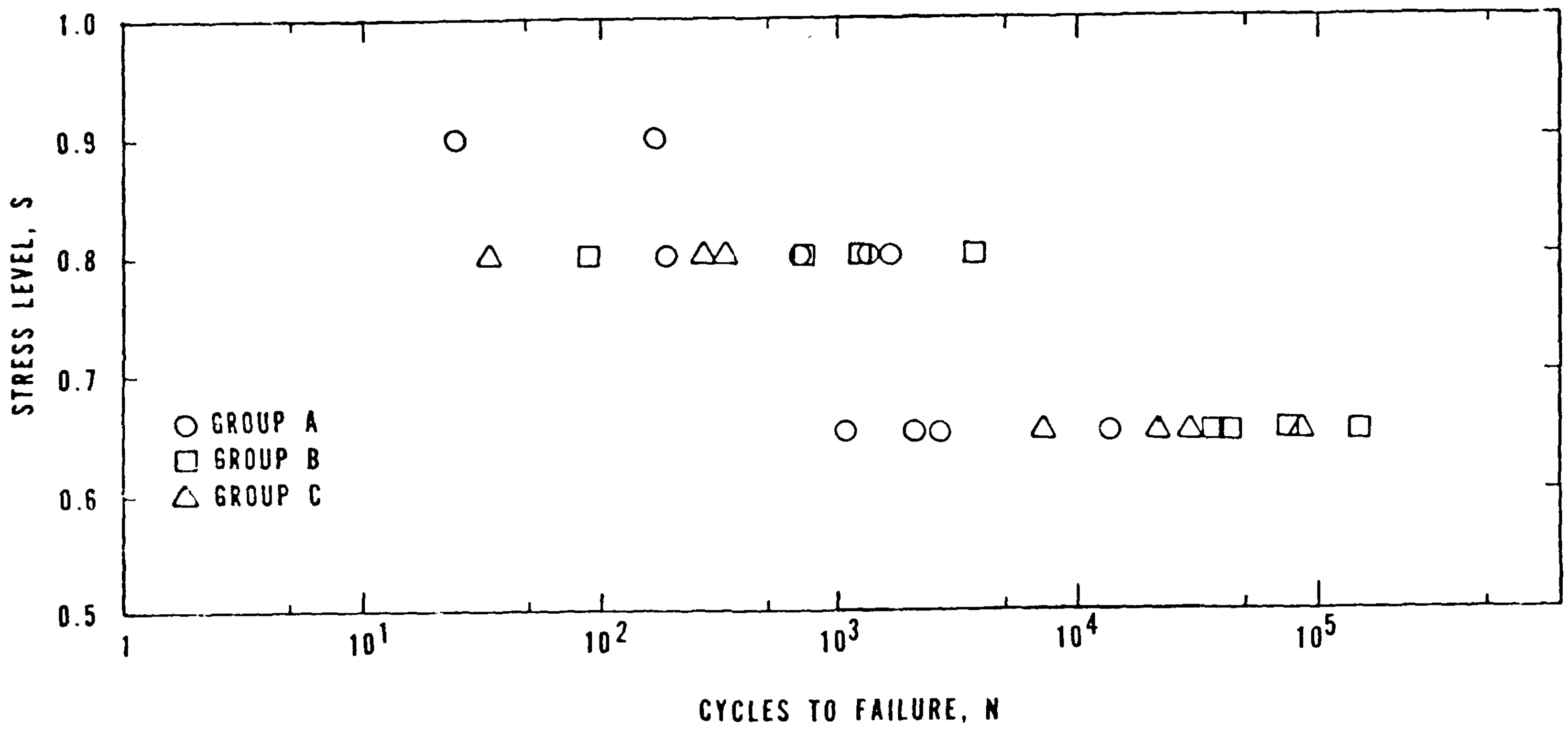

Figure 4. S-N Diagram for Flexural Fatigue of Polymer Concrete

An increase of only 15 percent for the modulus of rupture of polymer concrete for a rate of loading increase from 1034 to 1,380,000 kPa/min (an increase of over one thousand times) appears small compared to a 2 to 13 percent increase for the modulus of rupture of PCC for a rate of loading increase from 1034 to 3447 kPA/min (an increase of only about 3.3 times). The increase of modulus of rupture for PCC, however, is linearly related to the logarithm of rate of loading. If the same is true for polymer concrete, a 15 percent increase in modulus of rupture for a rate of loading of 1,380,000 kPA/min would correspond to a 2.5 percent increase for a 3477 kPa/min rate of loading. This increase would be within the range of increases for PCC.

2.2 Fatigue Testing

The S-N plot of the fatigue test results are shown in Figure 4. The scatter of data is typical for fatigue testing. Because of the variability of fatigue test results, it has become customary to describe fatigue behavior in terms of probability of failure. The data is analyzed by ranking the specimens in the order of cycles to failure for each stress ratio, and calculating the probabilities to failure, P, by dividing the rank of each specimen, m, by (n + 1), where n equals the total number of specimens tested at the particular stress ratio.

Graphical and mathematical techniques for obtaining the S-N-P relationship have been described by McCall (Reference 9). For a mathematical S-N-P relationship, an equation of the form

$$L = 10^{-aS^b(\log N)^c} \quad (10)$$

has been successfully used to describe the fatigue behavior of PCC (Reference 10). In Equation (10), S is the stress level previously defined, N is the number of loading cycles, and a, b, and c are experimental constants. Instead of using P, the probability of failure, the equation uses L, the probability of survival, which equals unity minus the probability of failure (i.e., L = 1 - P). The reason for changing from P to L is because this simplifies the form of Equation (10).

Equation (10) is linearized by taking logarithms of the logarithms of both sides of the equation and then rearranged to predict the cycles to failure for a given stress level and a certain probability of survival. The result is expressed as

$$Z = A + BX + CY \quad (11)$$

where $Z = \log \log N$, $X = \log S$, and $Y = \log(-\log L)$. The experimental constants of Equation (10) are related to the constants of Equation (11) by $a = 10^{-A/C}$, $b = -B/C$, and $c = 1/C$.

A multiple linear regression analysis was performed to determine the constants in Equation (11). Since there were only four or less data points for a given loading waveform at a given stress level, it was decided to combine the data of all the loading waveforms for a given stress level. The values of N, S, and L used for the regression analysis are listed in Table 3. The two data points for the stress level of 0.90 were deleted from the analysis since only two values may not be representative of the fatigue life at a particular stress level.

TABLE 3 - DATA USED FOR REGRESSION ANALYSIS OF POLYMER CONCRETE FATIGUE

rank, m	Number of cycles to failure, N, and probability of survival, L*, for a stress level, S			
	S = .80		S = .65	
	N	L	N	L
1	34	.92	1,067	.92
2	90	.83	2,039	.85
3	192	.75	2,585	.77
4	278	.67	7,016	.69
5	328	.58	13,784	.62
6	689	.50	21,417	.54
7	690	.42	29,149	.46
8	1290	.33	36,310	.38
9	1310	.25	43,010	.31
10	1678	.17	72,690	.23
11	3610	.08	85,381	.15
12	-	-	147,720	.08

$$*L = 1 - \frac{m}{n+1}$$

The results of the regression analysis in the form of Equation (11) is

$$Z = 0.317 - 2.27X + 0.206Y \qquad (12)$$

This equation is compared with the test data in Figure 5. The multiple correlation coefficient was calculated to be 0.989 indicating the equation is a good representation of the test data.

The results of the regression analysis were used to calculate the constants of Equation (10) and yields

$$L = 10^{-.0289S^{11.0}(\log N)^{4.86}}$$

Since the data for the different waveforms was combined for the regression analysis, the probabilities calculated by Equation (13) include the variability of loading waveforms used for testing. This is a useful relationship, however, because polymer concrete used for rapid runway repairs would be subjected to a variety of loading waveforms since aircraft would be traveling at different speeds and spacings. Thus, frequency and rest periods would vary considerably.

Equation (13) is valid only within the range of parameters tested and should not be used to predict results for stress levels above 0.80 nor below 0.65. Likewise, the equation is only valid for the range of frequencies and rest periods, as well as specimen size and temperatures, used for this testing program.

Influence of Loading Frequency - Kesler (Reference 11) found that the frequency used for fatigue testing of PCC had negligible effect on fatigue strength for frequencies between 70 and 440 cpm (1.17 to 7.33 c/s). The same cannot be said for polymer concrete

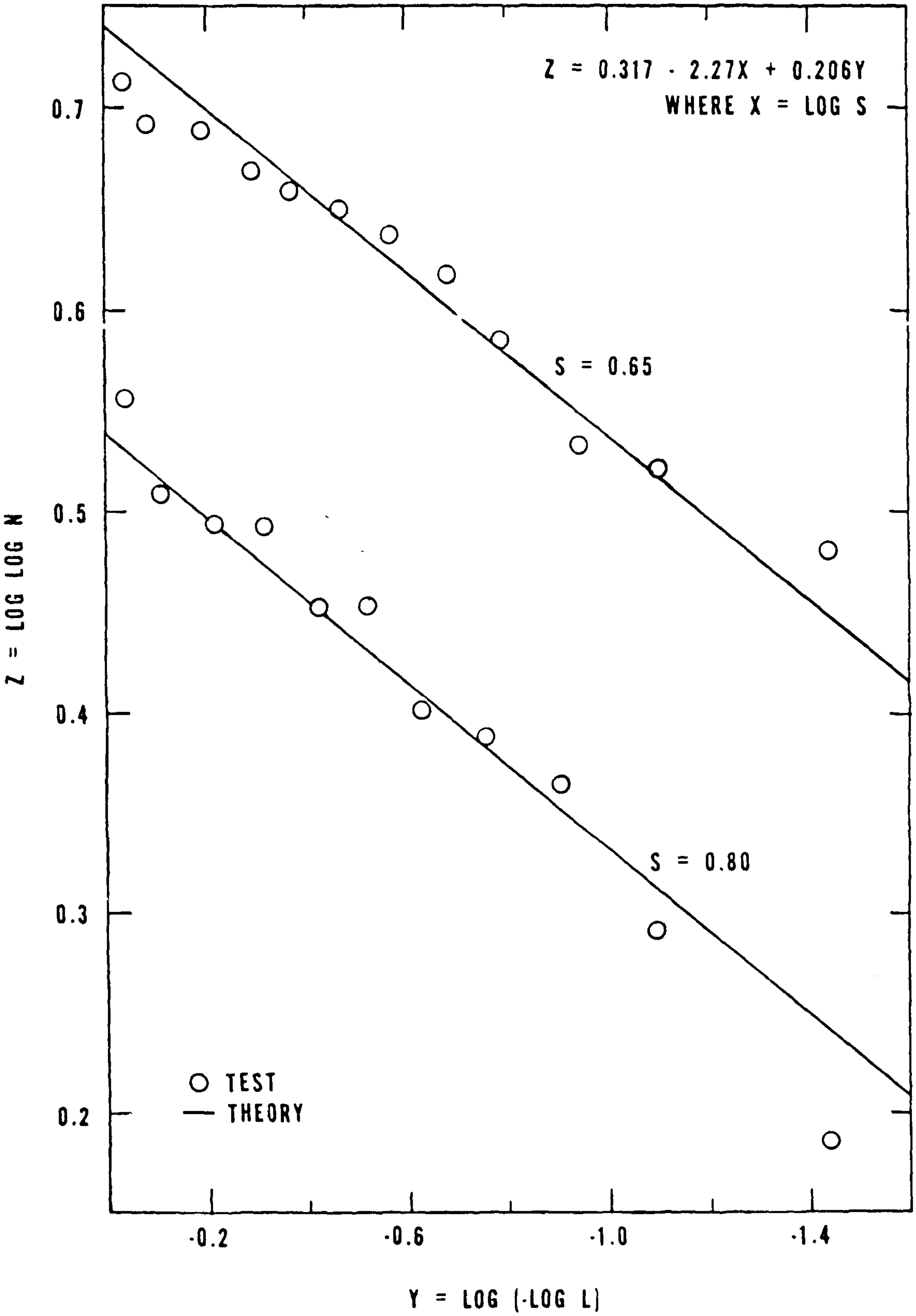

Figure 5. Comparison of Observed and Calculated Values for Fatigue of Polymer Concrete

The data plotted in Figure 4 shows a definite difference at a stress level of 0.65 between specimens tested at a frequency of 0.5 c/s compared to those tested at 10 c/s. Although too little data is available to determine if the difference is statistically significant, it can be concluded that frequency of testing is probably an important parameter. Therefore, in fatigue testing of polymer concrete, the frequency of testing should be treated as a variable when designing a testing program.

Influence of Rest Periods - Hilsdorf and Kesler (Reference 12) found that periodic rest periods increased the fatigue life of PCC. In their testing program, after every 4500 load cycles, the specimen was given a rest period of either 1, 5, 10, 20 or 27 min duration. It was found that for stress levels below about 0.70, fatigue life increased as the length of rest period increased up to 5 min. Further increases in the length of rest periods did not cause further increases of fatigue life.

Actual fatigue loading of airfield pavements includes a period of rest within each loading cycle. For this reason, such a waveform was used for group C specimens. In order to complete the testing within a reasonable period of time, a rest period of 0.9 sec. with a load pulse of 0.1 sec. made up the loading cycle. The data plotted in Figure 4 indicates a slight shift to a lower fatigue life at a 0.65 stress level, with the introduction of the rest period in the loading cycle. However, given the scatter of data, the differences in fatigue life may simply be due to the variability of the material rather than the introduction of the

rest period. Too little data is available to determine if the difference is statistically significant. In any event, longer rest periods are probably needed. But introducing a 5 min. rest period within each loading cycle would require 347 days for 100,000 loading cycles. Such testing is not practical and therefore the use of periodic rest periods, similar to Hilsdorf and Kesler, would have to be used.

In summary, the modulus of rupture of polymer concrete increases with rate of loading. The increase of modulus of rupture of polymer concrete was found to be within the range of increases for Portland Cement Concrete. Since a previous report concluded that a rupture failure of Portland Cement Concrete pavement caused by a single high magnitude load is unlikely at medium and high aircraft speeds (Reference 2), the same can be concluded for polymer concrete.

Equation (13) can be used to predict the probability of survival for stress levels and number of cycles to failure. However, the equation is only valid within the ranges of stress levels, loading frequencies, and rest periods, as well as the size of specimens and temperature used in this study.

Further testing is needed to statistically determine the influence of loading frequency and rest periods on the fatigue life of polymer concrete.

SECTION IV

ANALYSIS OF RIGID AND GRANULAR RAPID RUNWAY REPAIRS

The Air Force is currently investigating several techniques for rapid runway repairs. Because of the time constraints for completing the repairs, new pavement systems and materials are being considered.

It is the purpose of this section to analyze polymer concrete, sulfur concrete, and crushed limestone rapid runway repairs subjected to high magnitude dynamic loads.

1. POLYMER CONCRETE REPAIR

Based on the results of the fatigue testing discussed in Section III, polymer concrete has a relatively poor fatigue life. Specifically, the stress ratio decreases rapidly with increasing number of loading cycles. An analysis of polymer concrete repairs subjected to high magnitude dynamic loads must consider a fatigue failure. The results of twenty-four computer analyses using the BDR computer code are listed in Table 1 of Section II. The maximum tensile stresses from some of the results of the computer analysis are shown in Figure 6 along with dynamic load ratios for an F-4 aircraft.

The dynamic load ratio is defined as the high magnitude dynamic wheel load applied to the pavement due to aircraft response to surface roughness, divided by the static aircraft wheel load (static wheel load for the F-4 is 27 kips). Although Figure 6 shows dynamic load ratios up to 3.0, the highest dynamic

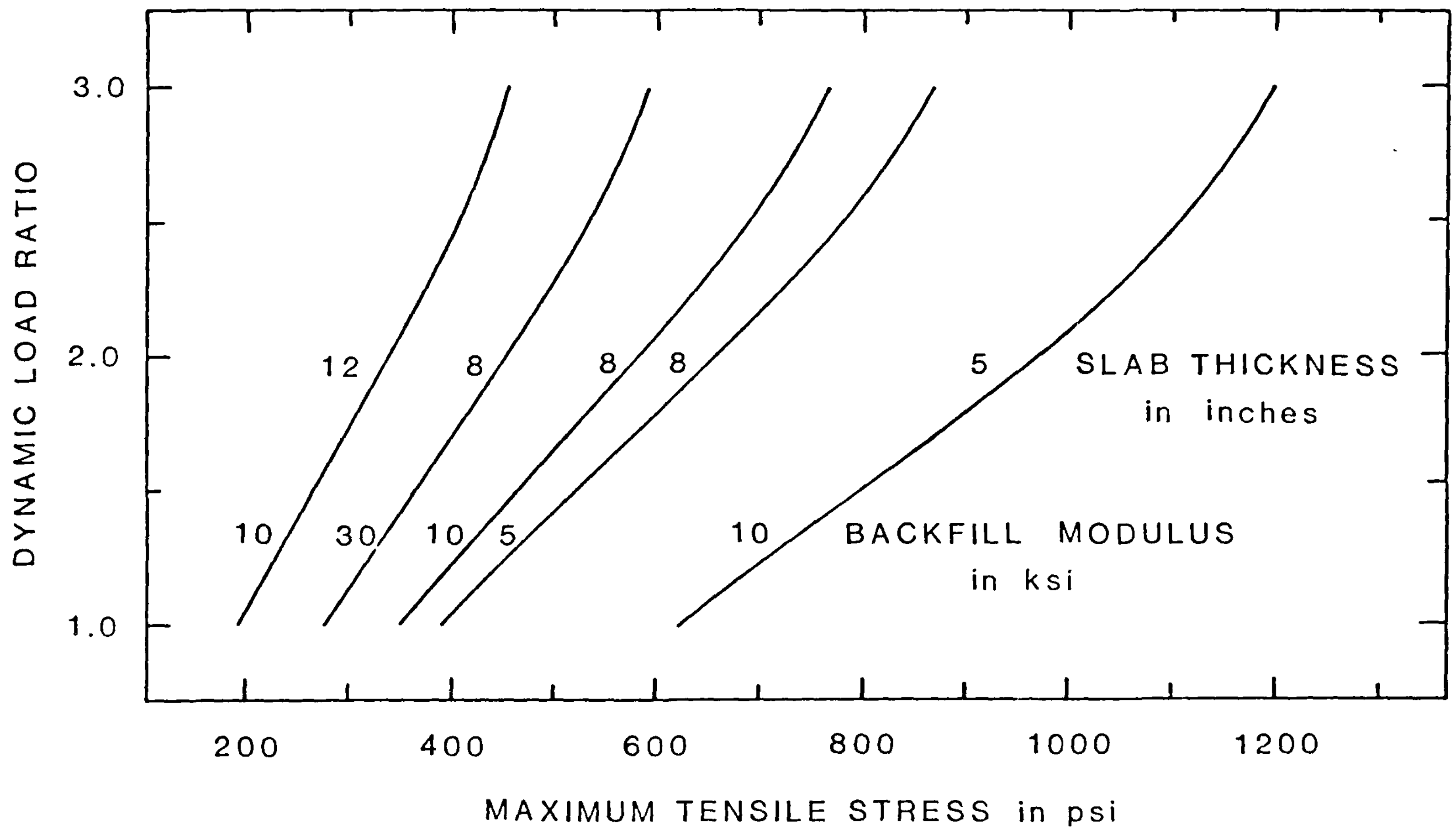

Figure 6. Maximum Rigid Slab Flexural Stress Versus Dynamic Load Ratio

load ratio which needs to be considered would be less than 2.5 since higher values would cause failure of the aircraft.

The modulus of rupture of Silikal^R polymer concrete computed from the average failure load of 7.43 kips from Section III is 2,477 psi. All of the tensile stresses in Figure 6 are less than one-half the modulus of rupture. If Equation (13) developed in Section III is valid for lower stress levels, a stress level of 0.50 with a probability of survival of 0.90 gives over 200,000 loading cycles before failure. The highest tensile stress listed in Table 1 is 1434 psi. This is the maximum stress computed from the BDR computer code and corresponds to a dynamic load ratio of 3.0, a slab thickness of 5 inches, and a resilient modulus for the subgrade (bomb damage debris backfill) of 5,000 psi. The stress level for the system would be .579 and for a 0.90 probability for survival, the number of load cycles would be 6,300.

The effect of aircraft speed on the number of loading cycles to failure depends on the effect of loading frequency on the fatigue life of polymer concrete, and, in some cases, the effect of loading frequency on the resilient modulus of the backfill and subgrade soil. As discussed in Section III, further testing is needed to statistically determine the influence of frequency of loading on the fatigue life of polymer concrete. To determine the resilient moduli of fine grained soils corresponding to different aircraft speeds, the loading frequencies to be used must be computed as outlined in Section II. The resilient moduli of

coarse grained soils is relatively independent of loading frequency (Reference 2).

The fatigue life for any of the aircraft-pavement systems analyzed is more than adequate for rapid runway repairs. Present BDR criteria requires about 7,000 passes, which would be less than 1000 coverages or loading cycles, over any one point on the pavement. In addition, because of variations in aircraft speed, the application of high magnitude dynamic loads would vary longitudinally along the pavement. Thus, the actual number of high magnitude dynamic loads applied to any point on the pavement would be further reduced. In summary, the repair would be designed for considerably less than 1000 load cycles, probably fewer than 100, for the anticipated high magnitude dynamic loads. However, because of the high modulus of rupture of polymer concrete, other failure criteria may limit the design.

2. SULFUR CONCRETE REPAIR

Sulfur melts at 239°F and when mixed with aggregate between 239°F and 320°F, a workable thermoplastic sulfur concrete results which can be placed like normal concrete. Because of the rapid gain in strength and the unusually high fatigue life of sulfur concrete, the Air Force is investigating it's use for rapid runway repairs.

Lee and Klaiber (Reference 13) investigated the modulus of elasticity, modulus of rupture, and fatigue life of several sulfur concrete mixes. The modulus of elasticity and modulus of rupture

of sulfur concrete are within the range of values of conventional portland cement concrete. But sulfur concrete does have drastically improved fatigue life, exhibiting an endurance limit above a stress level of about 0.90.

The moduli of rupture of sulfur concrete reported by Lee and Klaiber ranged between 435 to 590 psi. Since this is considerably lower than polymer concrete, flexural stress will control the design of sulfur concrete repairs. The design must be based on the maximum anticipated dynamic load ratio otherwise a rupture failure of the slab would result.

In order to avoid an overly conservative design, it is imperative that the beneficial effects of aircraft speed be taken into account. Specifically, the modulus of elasticity and modulus of rupture of sulfur concrete along with the resilient modulus of the bomb damage debris backfill must be determined at the duration and rate of loading corresponding to the aircraft speed at which the maximum anticipated dynamic load ratio occurs.

An accurate design and analysis of sulfur concrete repairs should also include the fatigue life of sulfur concrete. Specifically, a testing program similar to the one performed for polymer concrete discussed in Section III should be undertaken to develop an equation similar to Equation (13).

3. CRUSHED STONE REPAIR

The Air Force is currently testing a 24 inch lift of compacted crushed stone for rapid repair of runways. The failure

criteria is specifying a maximum allowable deformation. If deformations become large, surface roughness increases, which in turn increases the magnitude of dynamic loads to the aircraft and pavement repair.

Currently, failure criteria for crushed stone repairs looks only at permanent deformations, but elastic deformations are just as important in analyzing surface roughness. Ideally, field tests using load carts or aircraft at speeds greater than creep speed should incorporate a means of recording both elastic and inelastic deformations; several studies emphasize the importance of separating elastic and inelastic deformations when analyzing field test results (References 14, 15 and 16). This is important for tests involving any rapid runway repair for which deformations are important.

Twelve crushed stone repairs were analyzed using the BDR computer code. Maximum deformation and debris backfill vertical stress are listed in Table 4 for 18 and 24 inch thick crushed stone lifts for various wheel loads and backfill moduli. Some results are shown in Figure 7.

The computer analysis does not consider rutting since a suitable model has never been developed for crushed stone. Rutting in clays, silts, and sands have been modeled, but the interaction of a tire with coarse granular material is significantly different; development of such a model is beyond the scope of this study. However, the crushed stone repair requires installing a Foreign Object Damage (FOD) cover which would help to minimize rutting.

TABLE 4 - RESULTS OF BDR COMPUTER ANALYSIS OF CRUSHED STONE REPAIR

Debris Backfill Modulus (psi)	Aircraft Wheel Load (kips)	Deformation (inches)	Maximum Backfill Stress (psi)
	24 inch crushed stone thickness		
5,000	1.0	0.0523	2.7
5,000	2.0	0.0886	4.9
5,000	3.0	0.122	6.9
10,000	1.0	0.0407	4.5
10,000	2.0	0.0676	7.3
15,000	1.0	0.0359	6.1
15,000	2.0	0.0580	10.6
40,000	1.0	0.0285	10.3
40.000	2.0	0.0425	19.0
	18 inch crushed stone thickness		
5,000	1.0	0.125	5.0
5,000	2.0	0.199	9.7
5,000	3.0	0.269	14.2

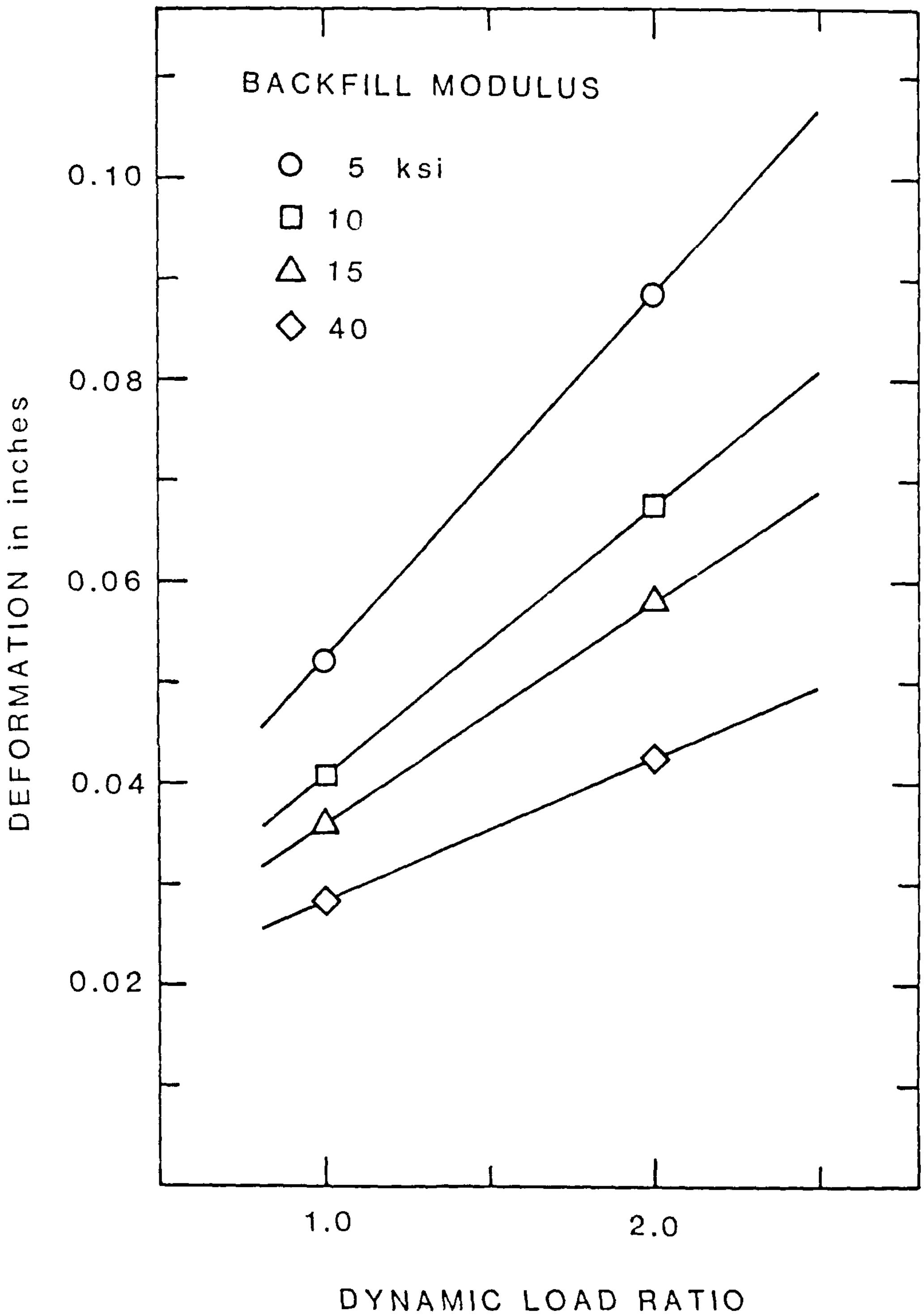

Figure 7. Crushed Stone Repair Deformation Versus Dynami~ Load Ratio

The rate and duration of loading have little influence on the dynamic modulus of the crushed stone layer itself (Reference 2). But the effect of aircraft speed can be very significant for crushed stone repairs because of the strong influence of bomb damage debris backfill modulus on deformations.

For fine grained soils (and perhaps bomb damage debris backfill), the rate and duration of loading may have a strong influence on the resilient modulus. Changes in dynamic material properties are closer to being linearly proportional to the logarithm of the rate and duration of loading and therefore linearly proportional to the logarithm of aircraft speed. For example, Wignot, et al (Reference 17) report test results for the complex modulus of a silty-clay at 90 percent saturation. The complex moduli of the soil were 2,000, 3,500, and 6,200 psi at frequencies of 0.16, 1.6, and 16.0 hertz respectively.

For a crushed stone repair example, assume the resilient moduli of the bomb damage debris backfill are 5,000, 10,000, and 15,000 psi at frequencies of loading corresponding to aircraft speeds of 1, 10, and 100 knots respectively. From Table 4, a 24 inch crushed stone repair yields a deformation of 0.0523 inches for a dynamic load ratio of 1.0 and backfill modulus of 5,000 psi. If the anticipated load ratio is 1.5 at aircraft speeds of 10 and 100 knots, the resulting deformations from Figure 7 would be about 0.054 (a 3% increase) and 0.046 (a 12% decrease) inches respectively. If deformation is the failure criteria, the repair would be satisfactory for the higher magnitude dynamic loads at the

higher aircraft speeds. If the anticipated dynamic load ratio was 2.0 at an aircraft speed of [illegible] knots, the backfill modulus would be about 12,500 psi (the logarithm of 30 is about halfway between the logarithms of 10 and 100), and from Figure 7, the deformation would be about 0.062 inches (a 10% increase). In this case, the high magnitude dynamic load governs the design.

In summary, for silt and clay subgrades and backfill, the resilient moduli of the soil must be determined at frequencies corresponding to aircraft speeds at which high magnitude dynamic loads are anticipated. This is because of the strong influence of the backfill modulus on the deformations of crushed stone repairs. For granular backfill, the resilient modulus of the soil is independent of frequency of loading and therefore no benefit can be expected from aircraft speed.

SECTION V

CONCLUSIONS

Based on the laboratory testing and computer analyses conducted for this investigation, the following conclusions are noted:

1. Design and analysis of rapid runway repairs subjected to large magnitude dynamic loads require that dynamic material properties be determined. Laboratory testing for dynamic material properties must be conducted at frequencies and load rates corresponding to aircraft speeds at which large magnitude loads are anticipated. Equations (1), (6), (7), (8), and (9) developed in this report can be used to calculate the frequency and duration of loading which correspond to an aircraft speed for a particular type aircraft and pavement system.

2. The modulus of rupture of polymer concrete increases with rate of loading; the increase is within the range of increases for Portland Cement Concrete. For the fatigue life of polymer concrete, there is a high correlation between experimental results and Equation (13) developed in this study which relates probability of survival with stress level and the number of cycles to failure. However, the equation is only valid within the ranges of stress levels, loading frequencies, and rest periods, as well as the size of specimens and temperature, used in

this study. Also, unlike Portland Cement Concrete, the frequency of loading probably effects the fatigue life of polymer concrete. More testing is needed to statistically determine the influence of loading frequency on the fatigue life of polymer concrete.

3. Because of the high modulus of rupture of polymer concrete, all of the aircraft-pavement systems analyzed in this report are more than adequate for flexural fatigue failure criteria. For example, a five-inch-thick polymer concrete slab on bomb damage debris backfill having a resilient modulus of 5,000 psi and subjected to an aircraft load of three times the static load can withstand 6,300 coverages with a 90 percent probability of survival. However, this result is restricted to the limitations of Equation (13); at low temperatures the results may be considerably different. Also, failure criteria other than flexural fatigue may govern the design.

4. The design of sulfur concrete repairs must be based on the maximum dynamic load. The modulus of rupture and fatigue life of sulfur concrete as well as the resilient modulus of the bomb damage debris backfill must be determined at the frequency and rate of loading corresponding to the aircraft speed for which the maximum dynamic load

is anticipated. Sulfur concrete repairs will be under designed if high magnitude dynamic loads are ignored and over designed if beneficial effects of aircraft speed are ignored when including high magnitude loads.

5. For crushed stone rapid runway repairs, the modulus of the bomb damage debris backfill has a strong influence on the dynamic response of the repair. If the resilient modulus of the backfill is sensitive to frequency of loading, the modulus must be determined at a testing frequency corresponding to the anticipated aircraft speed for which high magnitude dynamic loads occur as well as at a testing frequency corresponding to aircraft creep speed. Because of the strong influence of backfill modulus on the dynamic response of crushed stone repairs, either the static aircraft load at creep speed or high magnitude dynamic load at medium or high speeds may govern the design. If the resilient modulus of the backfill is independent of frequency of loading, no benefit can be expected from aircraft speed since the resilient modulus of crushed stone is independent of aircraft speed.

SECTION VI

RECOMMENDATIONS

1. Further fatigue testing of polymer concrete is necessary for the design of polymer concrete rapid runway repairs subjected to large magnitude dynamic loads. Specifically, an equation for the probability of survival should be developed which is valid for stress levels as low as 0.5, and incorporates temperature as a parameter since low temperatures may significantly alter the fatigue behavior of polymer concrete. Also, further testing is needed in order to satistically determine the influence of loading frequency and rest periods on the fatigue life of polymer concrete.

2. The dynamic behavior of sulfur concrete must be determined. Specifically, the influence of rate and duration of loading on the modulus of rupture, modulus of elasticity, and fatigue life of sulfur concrete must be known if sulfur concrete rapid runway repairs are to be designed and analyzed for large magnitude dynamic loads.

3. Laboratory dynamic testing of bomb damage debris backfill must be coordinated with load cart and aircraft field tests of all rapid runway repairs. This is essential if field test results are to be used in conjunction with the BDR computer code for the design and analysis of rapid runway repairs.

4. It is further recommended that load cart testing capabilities be developed which would provide for field tests using speeds of from creep to medium aircraft speeds and load capaci-

ties from static up to about twice the static wheel load. This is because of the sensitivity of the dynamic response of some pavement materials to vehicle speed. Ideally, these field tests should be conducted at various temperatures, since temperature is an important parameter. In addition, field tests should be designed so that both the elastic and inelastic responses can be determined.

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